The Issues & Challenges of 3D Managed Print Services: Towards a Support Tool for 3D Managed Print Services

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Abstract

Extrusion 3D printing has seen a rapid growth across many engineering sectors and is expected to triple in market value over the next decade. This is partly due to a step change in capability and increase in demand for the technology, and is leading to a requirement for 3D Managed Print Services (3D MPSs). This is where queues of prints are being received from multiple users and sent to multiple 3D printers. Examples of this include, Universities, where printers are being increasingly used in teaching, and the growing industry commonly referred to as Fabrication Laboratories (FabLabs).

Given the above situation, this paper argues that gaps exist in the capability of current software and support tools to offer appropriate support for 3D MPSs. To begin to address this, this paper discusses the key issues and challenges introduced by 3D MPSs, which continues into a proposition for a support tool for 3DMPSs. The paper then demonstrates the current development of this tool with the current focus of maximising 3D printer productivity. Through the application of this tool, it is proposed that a substantial gain in productivity can be achieved.

1. Introduction

Extrusion 3D printing has seen a rapid growth across many engineering sectors and is expected to triple in market value over the next decade [1]. Pioneered by the development of the RepRap 3D printer, an open-source project aimed at developing the first self-replicating machine, the industry has seen a sudden increase in the number of companies offering extrusion 3D printing solutions. Examples include MakerBot, 3D Systems, UP!, MostFun and M3D [2, 3].

The technology has now reached a stage of maturity whereby the reliability and cost of printing has made it a viable product for Universities to use in their teaching, and Fabrication Laboratories to use for the manufacture of parts & products by their customers [4]. In these contexts, multiple users send their prints to multiple printers on a daily basis. As an example, the University of Bristol currently has six 3D printers available for use by the students. This is being extended to 10 printers by the end of 2014 and is likely to be extended further in the years to come (Figure 1). This step change in both capability and demand has led to a requirement for 3D Managed

Printer Services (3D MPSs). However, the current strategies for submitting and monitoring 3DMPSs have been a developed on an ad-hoc basis, where significant manual input is typically required by the users.

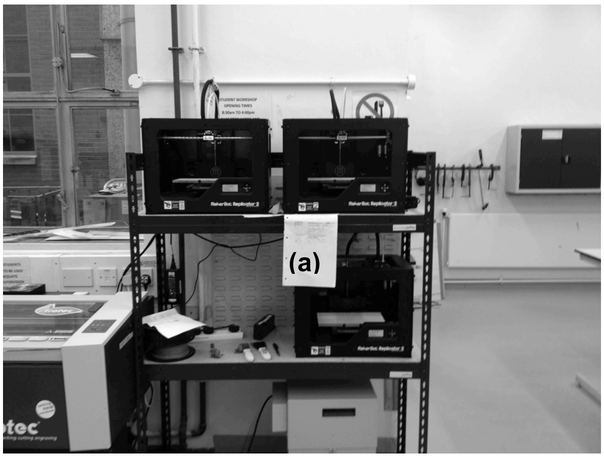

Figure 1: University of Bristol 3D MPS

Current software and support tools for 3D printers have been primarily focused on a single printer with the manual submission - be it through an online interface, laptop or SD Card - of prints by users once the printer becomes available (as illustrated in Figure 2). Expanding this process to 3D MPSs has often led to either a first come first serve basis or a manual allocation and ordering of prints. In both cases, there is an issue of meeting peak demand as well as extended periods of low utilisation (i.e. out-of-hours printing). For example, students at the university schedule through a manual paper-based scheduling chart and can only schedule prints during the university open hours (Figure 1, a).

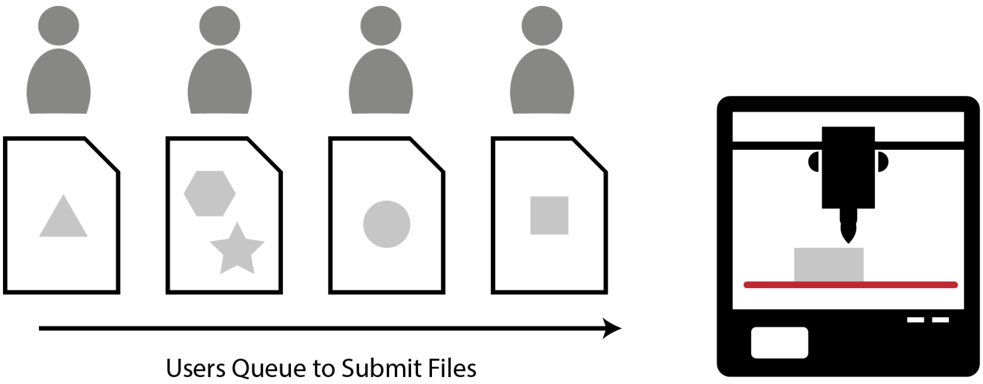

Figure 2: Illustrative Example of the Current 3D Printer Workflow

3D MPSs have to also consider the knowledge and experience of the individuals submitting prints. One of the main advantages of extrusion 3D printing has been its accessibility and ease-of-use for individuals. However this introduces a potential issue, where many of the individuals using extrusion 3D printing may not have the Design for Manufacture (DfM) experience and process knowledge in order to ensure the manufacturability of their prints. An example of this is the use of highly tapered parts that could lead to the extruding plastic missing the part and falling onto the printer bed. Currently, there is a lack of support tools that can verify the prints for manufacturability and this has led part failures as well as unnecessary costs for the 3D MPSs in terms of material waste and print time.

In addition, prints can fail due to issues arising from the machine itself. One example is plastic not being extruded. This could be because of a blockage, the inability for the machine to pull the plastic from the spool and/or the running out of plastic on the spool. Another is that a print fails due to calibration errors of the printer bed and this could be due to improper calibration during maintenance and/or losing calibration over time (a more exhaustive list of issues can be found at [5]). In all these cases, manual monitoring and intervention has been the common option as a means to combat these issues. This is because there is a lack of support tools that offer in-process monitoring of 3D printers and it is argued that this is placing unnecessary demands and stress upon staff to monitor prints, as well as limiting the use of printers out of working hours.

Although brief, this discussion has highlighted 3 key issues and challenges arising from 3D MPSs:

1. Verification of Product/Part Models to be Printed
2. Optimisation of 3D Printer(s) Productivity
3. Real-Time Condition Monitoring & Quality Control of 3D Printer(s)

To begin to address these challenges, this paper proposes a framework for a support tool for 3D MPSs alongside the potential objective functions by which one could assess the tool. This is followed by the current development of a tool that aligns to the framework. Finally, a discussion is made on the next steps and future work to assess the benefits provided by such a tool.

2. 3D MPS Support Tool

Figure 3 illustrates the 3D MPS support tool framework alongside the current development of a tool that aligns to the framework. It is envisaged that the users will be able to asynchronously submit files to a 3D MPS (potentially through a web service). The model presents a systematic workflow that addresses the above challenges in sequence. The first element in the sequence is the verification of the submitted part files. This is then followed by the optimisation of the productivity of the 3D MPS. The prints are then sent to the 3D printers where condition and quality control monitoring occurs. The following sub-sections discuss the challenges with respect to developing a solution as well as discussing the potential objective functions that one might assess the tool.

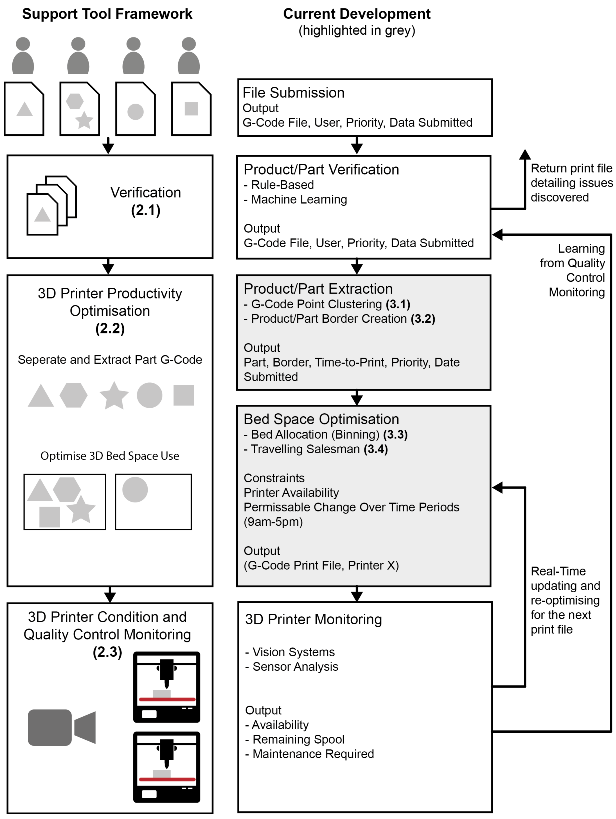

Figure 3: 3D Managed Print Service Optimisation Model

2.1. Verification

Upon submission, the initial step will be to verify the printability of the file and to immediately report back potential issues to the user. The objective function would be to minimise the number of unprintable prints sent to the printers. Potential methods to solve this could be through the application of machine learning techniques over a range of known successful and failed prints, as well as the application of rule-based systems that understand the dynamics & capability of the 3D printers.

2.2. Productivity Optimisation

Once the files have been verified, there is the opportunity to maximise the productivity of the 3D printers operating under the 3D MPS. In order to achieve this, a number of objective functions could be used. Minimising the number of changeovers required is one possible objective, as this would reduce the workload on the support staff as well as minimising non-printing time. In addition there may be constraints such as the changeovers having to occur during work hours rather than out-of-hours.

Also, maximising the use of the spool has to be considered to ensure minimal material waste. This can also be achieved through optimising the print bed space to ensure the maximum spool material use. In addition, identifying opportune times to change filament during the printing could be considered. This could be stopping the print at the stages where raft and supports are being printed and therefore, the changing of the filament at these stages will have little impact on the quality of the printed part.

The final aspect focuses on the individuals' prints and arrangement of parts in order to minimise non-printing time and the accuracy of the parts produced. In order to minimise non-printing during the print, one has to look at reducing the distance travelled between periods of printing. With regards to accuracy, one can look to minimise the time where multiple axes of movement occur (i.e. movement in both the x and y axis).

Thus, one of the key elements of this challenge is to be able to dynamically adjust the usage of the bed space in order to meet the objective functions described above. This is both in terms of fitting the appropriate number of parts with an optimum orientation and layout such as the time where the objective functions relating to when a changeover can occur and the amount of spool used are met.

2.3. 3D Printer Condition and Quality Control Monitoring

Focusing on the operation of the 3D printers, there is a challenge of providing real-time metrics of the printers condition. These can then be used in either the earlier challenges of verification and printer productivity as well as being able to provide notifications to the staff supporting the 3D MPS. There lies opportunities in deriving the relevant condition monitoring metrics for a 3D printer, such as remaining level of spool and current calibration, and the provision for dynamically correcting printer behaviour (automatic re-calibration, for example). In addition, there is the potential to automate the extraction of parts from the bed once the print has completed, which could greatly reduce the workload on support staff and impact optimisation of the 3D MPSs productivity.

One also has to consider developing real-time quality control where there are opportunities in being able to determine a parts quality in real-time and detect in-process quality issues. This could lead to the stopping of certain parts on the print bed from printing due to quality issues whilst continuing on with the rest of the parts on the bed. In addition, the results from the quality assessment could be immediately fed back into the verification element of the 3D MPS.

Given the challenges that have been encountered by 3D MPSs, this section has discussed the potential in addressing them through a 3D MPS support tool framework and has indicated eleven potential objective functions by which to assess the tool. These have been summarised in Table 1. This paper now focuses on the current development of a support tool that aligns to the framework and in particular, the strategy taken to extract product/parts from G-Code files and the optimisation of the 3D Printer bed space as part of the 3D Printer Productivity Optimisation.

Table 1: Potential Objective Functions for the 3D MPS Support Tool

Objective Function
Maximise 3D Productivity
Minimise Waiting Time for Users
Minimise Changeovers
Minimise Printer Movement
Minimise Empty Border Space
Maximise Part Accuracy
Minimise Required Computational Time
Maximise Correct Part Identification
Minimise Spool Waste
Minimise the Printing of Unprintable Prints
Minimise Non-Printing Time

3. 3D Printer Productivity Optimisation

For the current 3D print productivity element of the support tool framework, six assumptions/constraints have been made. These are as follows:

1. Users will be submitting the G-Code files for their prints to a central server where the optimisation can occur.
2. The G-Code files have been verified for printability.
3. The layer height is the same for each print.
4. There is no restriction on the changeover times
5. There is an unlimited spool on the 3D printer
6. There are no priorities assigned to the print files

Given the set of assumptions, the print productivity strategy has been split into four stages. The first looks at being able to extract and separate the individual part G-Code from a file that has been submitted by a user. Once all the parts have been identified and extracted from the user files, the second stage seeks to assign a border region around the part so that the parts can be re-organised based upon the bed space they require. Therefore, the third stage of the strategy is to optimise the use of the 3D print bed space given these borders. When the optimised bed space configuration has been established, the G-Code for each part is spliced together to form the print file. This also involves minimising the travel time between the parts that are being printed. Each stage is now discussed.

3.1. Part Extraction from G-Code

To extract the individual parts from the G-Code files, each file is parsed and processed individually. Figure 4 presents an excerpt of a G-Code file and shows the co-ordinates and other associated instructions that are used by the 3D printer to print a part. The initial step is to extract the x, y & z co-ordinate instruction sets from the file. This is achieved through regular expression matching

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G1 X105.400 Y-74.000 Z0.270 F9000.000 (Extruder Prime Dry Move)
G1 X-141 Y-74 Z0.270 F1800.000 E25.000 (Extruder Prime Start)
G92 A0 B0 (Reset after prime)
G1 Z0.000000 F1000
G1 X-141.0 Y-74.0 Z0.0 F1000 E0.0
G92 E0
G1 X-141.000 Y-74.000 Z0.000 F1500 A-1.30000; Retract
G1 X-141.000 Y-74.000 Z0.200 F1380; Travel move
M73 P0; Update Progress
G1 X-107.028 Y-68.889 Z0.200 F9000; Travel move
G1 X-107.028 Y-68.889 Z0.200 F1500 A0.00000; Restart
G1 X-107.028 Y-65.089 Z0.200 F1800 A0.13285; Inset
G1 X85.461 Y-65.089 Z0.200 F1800 A6.86224; Inset
G1 X85.461 Y-68.889 Z0.200 F1800 A6.99509; Inset
G1 X-107.028 Y-68.889 Z0.200 F1800 A13.72448; Inset
M73 P1; Update Progress
G1 X-107.428 Y-69.289 Z0.200 F1800 A13.74426; Connection
G1 X-107.428 Y-64.689 Z0.200 F1800 A13.90507; Outline
G1 X85.861 Y-64.689 Z0.200 F1800 A20.66243; Outline
G1 X85.861 Y-69.289 Z0.200 F1800 A20.82325; Outline
G1 X-107.428 Y-69.289 Z0.200 F1800 A27.58061; Outline
M73 P2; Update Progress
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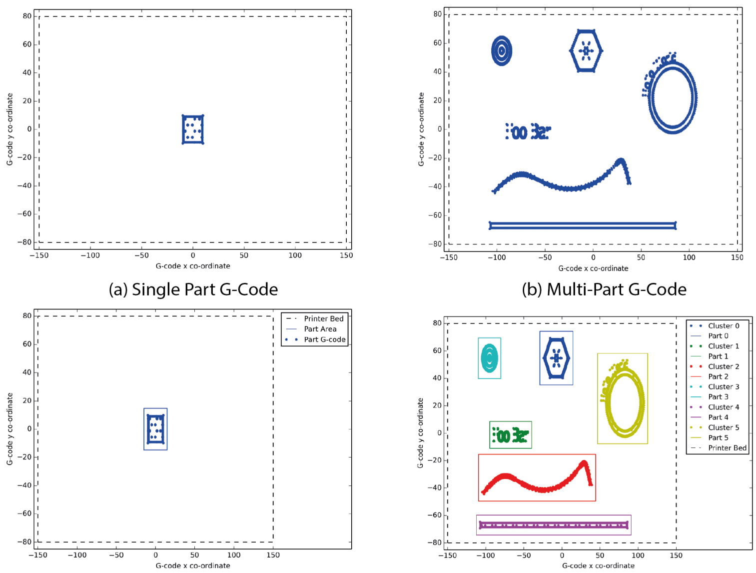
Figure 4: Excerpt from a 3D Print G-Code file

Once the co-ordinates have been extracted, common x, y, z co-ordinate sets that are produced for calibrating and setting the initial and final conditions of the 3D printer are removed. These have been identified through pattern matching common G-Code features that appear in all G-Code files sent to the 3D printers.

Figures 5a & 5b present the results from the extraction and cleaning of the G-Code co-ordinates for both a single and multi-part G-Code file. Although the G-Code of interest has been extracted, there remains the issue of identifying individual parts within the same file. To be able to identify the individual parts within a file, Density-based Spatial Clustering of Applications with Noise (DBSCAN) has been selected [6].



(a) Single Part G-Code

(b) Multi-Part G-Code

(c) Single Part Identification

(d) Multi-Part Identification

Figure 5: Part Identification from G-Code File

DBSCAN identifies clusters of points through the discovery of dense regions of points within an n-parameter space. In this case, the parameter space is the x, y co-ordinates within the G-Code file. Dense points are determined through the manual setting of two parameters: the search space (ε) and the minimum number of points to indicate a dense region (minPts). Each point (x) is iterated through in turn and the algorithm identifies the number of neighbouring points (n), which are the points within ε. If n > ε then x is determined part of a dense region. Once the points within a dense region have been determined, the algorithm then seeks to group points if the dense points are within ε of other dense points, and these become the clusters.

For this case, ε can be directly related to the millimetre spacing of the G-Code points and minPts being the number of G-Code points that will determine whether the point is within a dense region. The advantage of this clustering is that the number of clusters is not pre-determined. Rather, the algorithm generates the optimum cluster match. In addition, the algorithm can handle noise in that points do not have to be assigned to a specific cluster and this can be of benefit where there may be systematic points generated by 3D printer software, which are not related to the parts themselves. Although some cleaning has been performed before, this provides an additional measure to avoid unwanted G-Code being assigned to the various parts within a file. DBSCAN also makes no assumption on the shape of the cluster and thus, can identify complex geometries where other clustering techniques (such as K-Means) may struggle due to the underlying assumptions they make on the distribution of points within a cluster.

Figures 5c & 5d demonstrate the potential of DBSCAN to identify parts within the G-Code files. The parameters ε and minPts were set to 10 and 100, respectively. And as it can be shown through the colours of the various clusters, DBSCAN has been able to identify the separate parts within the G-Code file. However, further evaluation of this technique has to be performed on a greater range of part beds before a confirmation of the algorithms suitability can be confirmed. This is alongside a comparison with other clustering techniques with the objective functions being both the accuracy and speed of the part identification.

3.2. Assigning Part Borders

Given that the parts have been identified, borders can be created around the geometry that can then be used to determine the optimum bed space layout. The current procedure has been rule-based and involves selecting of the maximum and minimum x & y co-ordinates, and providing an additional five-millimetre spacing away from the part. These borders are shown on Figures 5c & 5d.

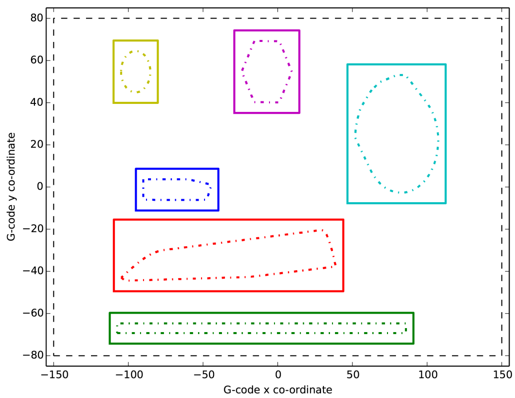


Figure 6: Comparison between Rule-Based (Solid Line)and Convex Hull Border Generation (Dot-Dash Line)

Although, it can be seen on some of the more geometrically complex parts that a significant amount of unnecessary space is being utilised to determine the borders. Therefore, future work could look to using borders generated through convex hulls and/or possibly using the pathway generating by the g-code itself to determine the outer borders of the parts [7]. Thus, greatly reducing the amount of unnecessary space being used to determine boundaries as demonstrated in Figure 6. Again, the objective functions for this stage could be to minimise the computational time on identifying the part border and to minimise unnecessary use of bed space to define the border. However, an additional caveat is the computational burden the border geometry may place upon the optimisation of the bed space in the following section.

3.3. Bed Space Optimisation

Since borders have been generated for the various parts and the bed space is of a known size, this problem lends itself to techniques that have been developed in the Bin Packing field. As the development of the support tool is still in its early stages, the First-Fit Decreasing Height (FFDH) algorithm has been applied as a proof of concept although many other techniques do exist [8].

In FFDH, the set of part borders generated from the previous stage are first ordered by the height (the length in the x-axis in this case). Once ordered, the borders are placed in that order such that the sum of the previous set of borders plus the next border to be placed does not exceed the width of the bin (the y-axis of the bed in this case). If this does occur, a new line is created starting at the maximum x length of the set of borders in the previous line.

Figure 7 displays the result of the FFDH on a set of parts attained from the DBSCAN clustering from three G-Code print files with the x-axis being the height and the y-axis being the bin width. The numbers (1-10) assigned to the parts indicate the order in which they were placed by ordering them by decreasing x. The letters (A, B, C) indicate the three layers that were generated on the bed. Given that these parts were originally from three separate print files, it is suggested that there could be a significant reduction in the number of changeovers required by optimising the bed space.

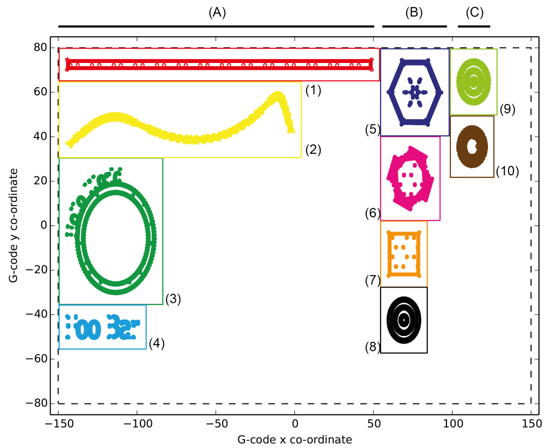


Figure 7: FFDH Optimised Print Bed

This current optimisation of the bed space has sought to maximise the use of the bed space. As discussed previously, further objective functions may have to be considered, such as maximising the use of the remaining spool and minimising waiting time for users depending on their print priority and time of file submission. In addition, the print must meet the constraints that may be in placed on changeover times due to working hours, for example. It is also the case that the algorithm that is applied for this optimisation is highly dependent upon the border shapes generated by the previous stage.

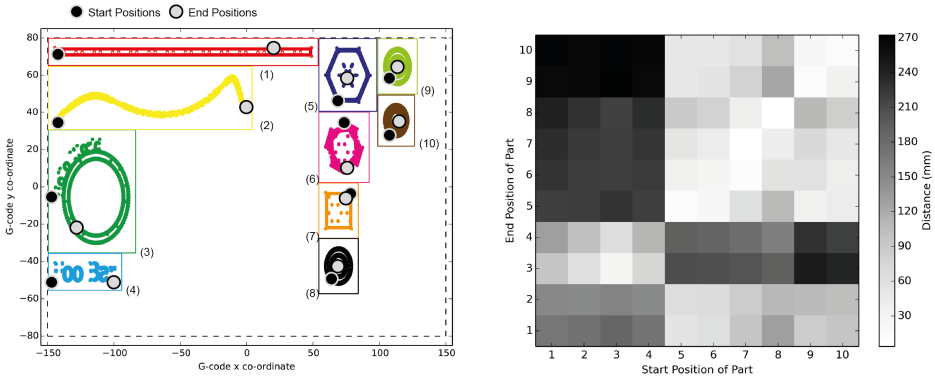
Upon achieving the optimum bed space where the selection of parts and their positions has been finalised, there is the final stage bringing the G-Code parts together to form the final G-Code file ready for submission to the 3D printers.

3.3. Splice G-Code to Form Final 3D Print Operation

As discussed previously, there are a number of common G-Code elements that reside in all 3D printer files regardless of the part(s) that are being printed. Therefore, the first step is to generate a template featuring these elements.

The next step is to start adding the individual part G-Codes into the template. This is done on a per layer basis and hence the constraint earlier of having a common layer height for all the parts being produced. Also, given the re-organisation of the parts, a translation of the original G-Code positions to the new locations is required.

Once completed, there is the final step of deciding the route the printer head should take between parts for each layer. This is slightly similar to the Travelling Salesmen Problem albeit with one caveat, which is that there are start and end positions for each part (as shown in Figure 8a). Figure 8b shows the distance matrix for the end and start positions of the various parts and the objective is to minimise the non-printing path between parts. In addition, there is the travel distance between the end and start position between each layer to consider.



(a) Start and End Positions for Each Part

(b) Distance Matrix between Start and End Positions

Figure 8: Travelling Salesman Problem between Parts

4. Next Steps & Future Work

This paper has uncovered the key issues and challenges facing 3D MPSs and has proposed a support tool framework alongside detailing the current development of a support tool that aligns to the framework. Although this paper has illustrated the potential benefits of supporting 3D MPSs through this framework, future work has to compare and contrast the various strategies for optimising the productivity of 3D MPSs. This includes looking at various methods of extracting parts, generating borders, assigning parts to bed spaces and optimise the route the printer head takes between parts.

In addition, there is a need to develop various evaluation datasets, the 3D print verification element and modelling of the 3D printers so that a multi-objective optimisation of the support tool can occur. Finally, it is the aim to open-source the development of the support tool in order to enable collaborative research within the field of 3D MPSs.

5. Conclusion

Extrusion 3D printing has seen a significant growth over the past decade and is likely to continue in the years to come. This has been partly due to the increase in their capability and the demand from consumer markets, and has led to the requirement of 3D Managed Print Services (3D MPSs).

This paper has discussed the three key associated issues and challenges that have arisen from 3D MPSs which are, verification, printer productivity and condition & quality control monitoring. In addition, it has been highlighted that current software/support tools do not currently cater for the needs of 3D MPSs.

To begin to address this, this paper has provided a 3D MPS support tool framework aimed specifically at overcoming the above issues and challenges. The paper has continued by reporting on the current progress that has been made in developing a support tool as well as discussing the objective functions and future work. Even at this early stage, initial indications show that a substantial gain in the productivity of the 3D MPS can be attained.

Acknowledgements

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